Evaluation of Soft Error Tolerance on Flip-Flops Restoring from a Single Node Upset by C-elements

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***Abstract*—Integrated circuits on automotive or aerospace applications must have high radiation tolerance. Multiplication such as duplication or triplication is effective for flip-flops (FFs). Clock gating may be used to reduce power consumption. Soft error tolerance depends on multiplexing, and soft error tolerance becomes weak by clock gating. We evaluate soft error tolerance of three types of FFs by α-ray and heavy ion irradiaiton test. According to the results of α-ray irradiation test, the soft-error tolerance of two FFs is 2x or 26x stronger than that of BCDMRFF. Heavy-ions irradiation test shows that the tolerance of the FF, which restore the errors, is 30x or more than that of BCDMRFF.**

***Keywords*—Flip-Flop, Soft error, Reliability, Radiation-hard**

I. INTRODUCTION

Integrated circuits for automotive or aerospace must have not only high performance, but also reliability against soft errors. Soft error is a temporary fault in which the stored value of a storage element is flipped by a radiation particle hit. The main sources of soft errors are α particles and neutrons in the terrestrial region and heavy ions in outerspace. A radiation particle inrushing to the transistor causes the output voltage to be unstable and flips the stored value of a storage element, which called single node upset (SNU). Circuit redundancy is one of effective soft-error mitigation techniques. TMRFF [1], BISERFF [2], and BCDMRFF [3] are redundant FFs that have high soft-error tolerance. The soft-error tolerance of BCDMRFF to heavy ions is 10–100 times better than that of the standard FF [4]. Power consumption is also important for aerospace applications. Clock gating (CG) is one of the methods to save power consumption. If the FFs are unable to restore the faults, the soft-error tolerance is reduced because errors are accumulated under CG. In order to enhance soft-error tolerance even under CG, FFs in which stored values are not easily flipped or automatically restored are mandatory.

In this paper, we propose two types of radiation-hard FFs under CG by adding wires or elements to BCDMRFF. The proposed FFs were fabricated in a 65 nm bulk process. We evaluated the soft error tolerance of FFs by α-ray and heavy ion irradiation test.

II. PROPOSED FLIP-FLOPS

A. Adding wires to clocked inverters

Fig. 1 shows the proposed Bistable Cross-coupled Transmission Gate Flip-Flop (BCTGFF). In the proposed FF, the clocked inverter, which is most vulnerable to soft errors in the latches, is split into an inverter and a transmission gate. This structure increases the critical charge (Q_{crit}) [5]. Q_{crit} is the minimum charge required to flip a stored value. Soft errors are more likely to occur on nMOS transistors than on pMOS transistors, becasue the mobility of electrons is larger than that of holes [6]. Thus, the Q_{crit} of nMOS is shown in Table I. Q_{crit} of BCTGFF increases by more than 3 fC at all points.

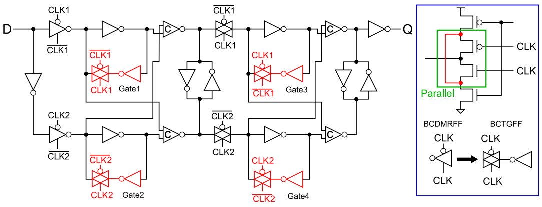

Fig. 1: Bistable Cross-coupled Transmission Gate FF

TABLE I: Comparison of Q_{crit}[fC]

FF	Gate1	Gate2	Gate3	Gate4
BCDMRFF	6.0	6.0	6.0	6.0
BCTGFF	10 (+4.0)	9.5 (+3.5)	9.0 (+3.0)	9.0 (+3.0)

B. Adding C-elements to each latch

Another proposed FF is Quadrupe-C-element Cross-coupled Flip-Flop (QCCFF) is shown in Fig. 2. The weak keepers (WKs) of BCDMRFF are removed in QCCFF. Instead of the WKs, QCCFF has C-elements in each latch. The C-elements in the latches remove a error and restore flipped value. The delay overhead of QCCFF is smaller than BCDMRFF because the number of gates from the input to the output is reduced.

C. Comparison of Area, Delay, and Power

The area, delay, and power of the FFs in a 65 nm bulk process are shown in Table II. Note that the values in the table are normalized to BCDMRFF. Table II shows that the performance overheads of BCTGFF are small since BCTGFF is constructed by adding a few wires to BCDMRFF. The

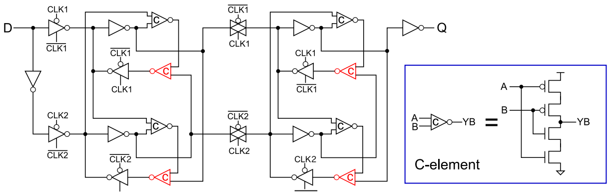

Fig. 2: Quadruple-C-element Cross-coupled FF

TABLE II: Comparison of Area, Delay, and Power

FF	Area	Delay	Power	ADP
BCDMRFF	1.00	1.00	1.00	1.00
BCTGFF	1.00	0.98	1.00	0.98
QCCFF	1.11	0.87	1.04	1.00

area of QCCFF is increased by 10% compared to the area of BCDMRFF because QCCFF contains 8 more transistors than BCDMRFF. The delay time is reduced by 13%, because the number of stages from input pin to output pin in QCCFF is less than that in BCTGFF.

III. α-RAY AND HEAVY-ION IRRADIATION TEST

The soft error tolerance of the proposed FFs is evaluated by a α-ray source (3 MBq ^{241}Am) and Kr irradiation test. The α-ray irradiation test was performed 160 times for 120 seconds. The Kr irradiation test was performed 40 times for 10 seconds. The α source was kept on putting on the DUT during initialization (INIT) and readout (RO). In the Kr irradiation, Kr ions were not irradiated during INIT and RO.

A. α-ray irradiation results

Fig. 3 shows the results of α-ray irradiation test. Both of the proposed FFs have fewer soft error rates (SER) than BCDMRFF. Soft-error tolerance becomes stronger if SER becomes smaller. BCTGFF is 2x stronger than BCDMRFF, because of larger Q_{crit} as shown in Table I. QCCFF is 26x stronger than BCDMRFF, because the errors are restored and not accumulated due to this latches.

QCCFF has some errors by the α-ray irradiation. This is becasue the α-ray source was kept to put on DUT. Fig. 4 shows the comparison of the error probabilities (P_{error}) of irradiation for 120 seconds and irradiation during INIT and RO. Irradiation for 120 seconds includes INIT and RO phase. In QCCFF, P_{error} of irradiation for 120 seconds is equal to irradiation during INIT and RO. This means that soft errors occurred during the INIT and RO. This is because the vulnerable standard FFs are involved in the shift registers in the fabricated chip. Thus, QCCFF has high soft-error tolerance by the α-ray irradiation under static conditions, because all errors occur during INIT and RO.

B. Heavy ion irradiation results

Cross section (CS) of Kr irradiation test are shown in Fig. 5. CS means the area of upsets when a radiation particle passes through a circuit. Soft-error tolerance become stronger if CS becomes smaller. According to Fig. 5, the soft-error tolerance of BCTGFF is different by each (Q, CLK). At (Q, CLK) = (0, 1), BCTGFF is 1.5x stronger than BCDMRFF, while it is weaker than BCDMRFF at (Q, CLK) = (0, 0). QCCFF has errors only in the primary latch (PL). Its soft-error tolerance is 30x or more than that of BCDMRFF. The tolerance of the scandary latch (SL) of QCCFF is much higher than PL, because QCCFF has no error in SL. This result shows that the FF, which automatically restores the failure, exhibits higher soft-error tolerance that can be used for automotive and aerospace applications.

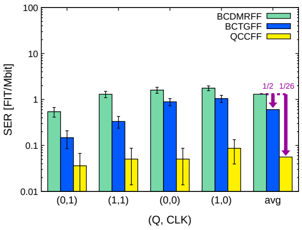

Fig. 3: The SER of α-ray irradiation during 120 seconds

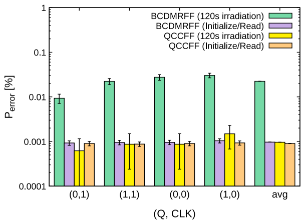

Fig. 4: The P_{error} of irradiation for 120 seconds or INIT/RO

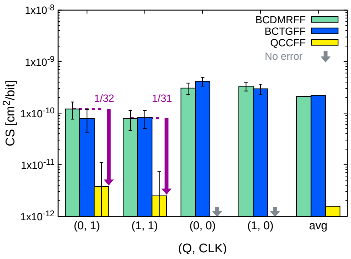

Fig. 5: The CS of Kr irradiation for 10 seconds.

IV. CONCLUSION

In this paper, we propose BCTGFF and QCCFF, which have high soft-error tolerance under CG and evaluate their tolerance by irradiation tests. The α-ray irradiation test reveals that the soft-error tolerance of the proposed FFs is higher than that of BCDMRFF. According to Kr irradiation test, the tolerance of BCTGFF is different by each (Q, CLK). In contrast, QCCFF is 30x or more stronger tolerance than BCDMRFF. Thus, QCCFF exhibits high soft-error tolerance enough to be used for automotive and aerospace applications.

ACKNOWLEGMENT

This study is supported by Socionext Inc. EDA tools used for simulations and layout design were provided Cadence Design Japan Ltd, Synopsys Japan Ltd, and Siemens EDA Japan Ltd through d.lab-VDEC of the University of Tokyo.

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